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Energy recovery systems for retrofitting in internal combustion engine vehicles: A review of techniques

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ABSTRACT

Energy recovery systems (ERSs) for internal combustion engine vehicles (ICEVs) are reviewed in the context of fuel efficiency improvement and retrofit capabilities. The paper presents technical knowledge on the potential benefits that retrofitted ERSs may achieve in carbon emissions reduction. A first distinction of ERSs is made between the sources of the energy and further sub-divided on the technique to harvest and store the energy. A critical evaluation is performed on the associated characteristics such as weight, size and cost. Finally, the paper summarizes the ERSs technologies under a number of common criteria, and finds out, that the most effective ERSs in terms of fuel efficiency are the ones more difficult to retrofit. Further research is suggested to investigate the trade-off between fuel consumption reduction and investment cost of the system.

Contents

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1. Introduction

Energy recovery systems (ERSs) for automotive applications are defined as the techniques to recover the energy of the vehicle that otherwise would have been wasted. The recovered energy can be stored and then used when necessary, reducing the need for further energy source or fuel, and therefore improving the overall efficiency of the vehicle. ERSs may be applied in a vast range of technologies within powertrains for automotive industry. It is only ERSs that potentially offer short and medium term solutions to the problem of vehicle population growth and the associated emissions. Within the European Union (EU), emissions from road transport are estimated 23% of the total CO_2 levels. To reduce car pollution, the EU has set targets for average CO_2 tailpipe emissions at 130 and 95 gCO_2/km for 2015 and 2020, respectively. However, with the 2009 average actual tailpipe CO_2 emissions at 145.7 gCO_2/km, there are challenges in retrofitting, cost and impact on the whole vehicle system and within the transport system [1,2].

1.1. The market

The field of energy recovery (ER) has been the subject of research and innovation in patents since the 1970s [3–5]. However, the automotive industry has normally focused in more traditional fields to enhance the fuel efficiency of vehicles, such as engine efficiency or aerodynamics. It is only in recent years that manufacturers have realized that ERSs present a cost-effective alternative to improve efficiency, and therefore the potential benefits of those systems are being fully developed.

In fact, ERSs are currently found in some vehicle models, regardless of the type of powertrain. Manufacturers such as BMW and Renault already integrated ERSs in internal combustion engine vehicles (ICEVs) [6,7]. On the other hand, hybrid electric vehicles (HEVs) such as Toyota Prius and battery electric vehicles (BEVs) such as Nissan Leaf already feature kinetic energy recovery systems (KERSs) within their powertrain also known as regenerative braking technique [8,9]. In an automotive industry clearly focused on efficiency gains, the increasing number of new vehicles performing ERSs highlights the benefits obtained by this technique in terms of energy usage.

In the United Kingdom the financial incentives for alternative vehicles have doubled the sales for HEVs from 2007 to 2012. However, the market share has only been rising slowly from 0.7% to 1.3% [10], while BEVs have shown even more marginal results [11]. In spite of the increased sales of EVs and associated financial support schemes as well as the technology promise of fuel cell vehicles (FCVs), their world market penetration will not be significant in the short and medium terms. This is illustrated in Fig. 1, showing the sales forecast for passenger light duty vehicles (LDVs) under the International Energy Agency (IEA) BLUE Map scenario and based on a 50% fuel efficiency improvement by 2050 over 2005 levels. EVs and FCVs would not be majority in the vehicle parc, the population of vehicles on the road, until 2065–70 considering a realistic LDV lifetime of 15–20 years [12].

In addition, major markets such as in the EU and the United States (US), new vehicle sales figures are not expected to increase significantly while second hand vehicle market is on the rise. In the EU the vehicle parc increased but sales fell short since 2007 [13]. This would allow a greater impact in emissions on the current vehicle parc and motivation towards retrofit systems to enhance efficiency in the sector.

1.2. The sensitive HEVs and BEVs role on GHG reductions

Life cycle analyses (LCAs) for vehicle technologies have mostly taken the full approach from cradle to grave. That is, taking into account not only the emissions related to the use of the vehicles but also the associated emissions to manufacturing and disposing. A common approach in these studies for the life cycle impact assessment (LCIA) method is the quantification of the equivalent green house gas (GHG) emissions, which are a measure for global warming potential (GWP). These LCA studies have demonstrated that the potential benefits of HEVs and BEVs over conventional ICEVs depend on a number of variables, and in particular cases they may not demonstrate a clear advantage [14–17].

LCA studies have shown that GHG emissions associated to the manufacturing process are higher in HEVs than in ICEVs. However, this difference may be offset during the usage phase of the vehicle, attributed to the increased fuel efficiency of HEVs. For instance, for a typical HEV at an annual mileage of 10,000 km, it would require 5 years to offset the extra GHG emissions associated with manufacturing over the ICEV, which may be achievable for an average driver [14,15]. However, if an existing ICEV, that has a residual value, is replaced by an HEV, the offset period would increase up to 14 years due to all the manufacturing emissions.

BEVs have shown even higher GHG emissions associated to the manufacturing process than HEVs, which requires a greater offset [14,15]. However, emissions associated to the usage phase of BEVs strongly depend on how the electricity is produced. For instance, a BEV sourced with low-carbon electricity, such as renewable

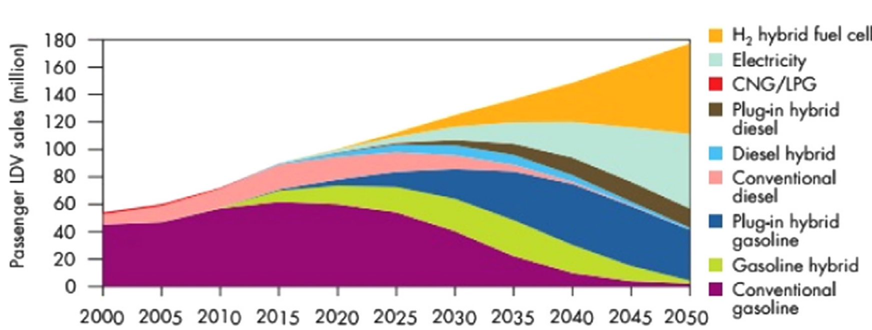

Fig. 1. IEA market forecast [12].

energy, shows a far lower GWP value than conventional ICEVs, but on the other hand, coal-based electricity production would make ICEVs and HEVs to perform similar or even better in terms of GWP than BEVs [15,18,19]. At the current situation of energy production, with many countries relying on fossil fuels, such as 77% in the United States and 71% in the United Kingdom the advantage of BEVs in terms of GWP may become questionable [19]. The future evolution of electricity production to low-carbon sources suggests that BEVs and other plug-in HEVs could improve their values of GWP. However the transformation of the energy sector will not occur in the short term.

In addition, the deployment of EVs brings along other issues. Batteries and motors use new rare-earth elements (REEs). The increased exploitation of these REEs can be political and environmentally challenging [20–22]. And, the proposed mandatory EU targets for charging stations at each member state have also increased pressure on the infrastructure [23].

1.3. *Lifetime of vehicles*

Life span of vehicles, currently averaged around 13 years, is an important variable in GWP calculation. The most carbon-intensive processes in the life of a vehicle are fabrication and usage phase [15,16]. The latter is directly related with the mileage, which in turn is linked with the life span of the car.

Nowadays, triggered by the economic downfall in automotive industry, it became common practice in policies to encourage the replacement of existing vehicles for more modern and efficient ones. Normally a dual objective is pursued (i) to stimulate the economy and (ii) to diminish the emissions. These support schemes tend to shorten the average life span of the vehicle parc [24]. However, contrary to these dual-objective scheme, studies have found that actually extending the lifetime of vehicles could lead to improve the economy and diminish both energy use and carbon emissions [25,26].

1.4. *Retrofitting ERSs, a short to medium-term opportunity*

With the increased vehicle parc, it is undeniable that the way forward is through transport electrification. The deployment of EVs in the medium term will reduce carbon emissions as long as the shift is produced naturally, allowing existing vehicles to finish their expected life span. In the long term, the increase of less carbon-intensive electricity production could allow BEVs to achieve further reduced values of GWP. However, according to vehicle sales forecasts, the dominance of ICEVs in the vehicle parc is here to stay until around 2065.

Therefore, the retrofitting low-cost ERSs is a short to medium term opportunity, allowing existing vehicle parc to increase efficiency and extend its lifetime which will contribute to the reduction of GHG without significant investment and within a short period of time.

1.5. *The ideal ERS*

From the technical perspective, an ideal ERS should harvest the energy from a plentiful source and perform a high ratio of energy recovery. Ideally, the energy has to be harvested continuously, and the efficiency gain has to be significant in all driving conditions. Hence the ERS should be able to store all the potentially recoverable energy and released back this energy stored efficiently.

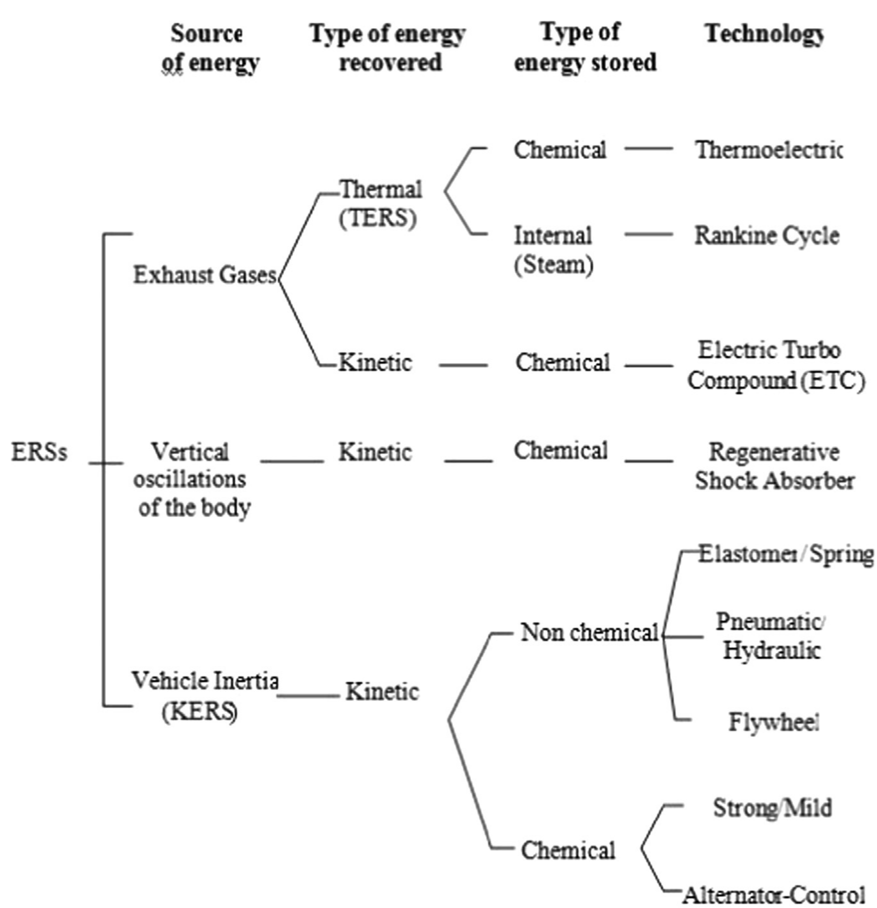

Fig. 2. Classification of ERSs for automotive applications.

In addition, it should not add significant weight or space requirements. It should use as much existing parts as possible, and if new components were necessary, they should be inexpensive, recyclable, non-toxic and low energy embedded. Ultimately, it should be easy to retrofit, with no major modifications needed for the implementation of the system.

1.6. Aim of this review

The aim of this paper is to provide the reader with an extensive overview of the ERSs for ICEVs. Special attention is given to the accurate classification of the different systems and to the suitability of a given technique for retrofitting. This review will provide insight into the use of ERSs, as well as awareness about the potential benefits of a retrofit system. It is expected this will inspire individuals, business and policy makers to allow deployment of these ERSs to enhance efficiency in transport and consequently contribute towards GHG emissions reduction.

The paper is structured as follows. In Section 2, the ERS techniques are classified and are discussed extensively. Key findings are summarized in Section 3. Finally, in Section 4, the main conclusions are presented.

2. Energy recovery systems techniques

In the present review article, ERSs are firstly classified according to the source of energy to be recovered: (i) energy from exhaust gases, (ii) energy from vertical oscillations of the body and (iii) energy from vehicle inertia as shown in Fig. 2. Following the first classification, the techniques are further sub-classified according to type of energy recovered, storage and technology.

2.1. Energy recovery from exhaust gases

In an internal combustion engine (ICE), exhaust gases are released at high temperature and velocity. Thus, ERSs based on this energy source may further aim for thermal energy recovery or kinetic energy recovery. The fact that the exhaust gases are released continuously means that the energy can be recovered all the time the engine is working.

2.1.1. Thermal energy recovery systems (TERSs)

An ICE continuously releases about two-thirds of the energy contained in the fuel as heat [27,28]. TERSs recover part of this heat so the energy can be stored and reused. In TERSs, the energy recovery may be achieved by two technologies using (i) thermoelectric generator and (ii) Rankine cycle.

2.1.1.1. Thermoelectric TERS. These systems use a thermoelectric generator module (TGM) to produce electricity from the waste heat released through the exhaust [29,30]. This TGM unit can be placed in the engine bay or in the middle section of the exhaust. The power produced, estimated around 700 W, can be used to feed the electrical auxiliaries of the vehicle or to charge the battery. Fig. 3(a) illustrates the operation of a thermoelectric TERS. Studies have demonstrated fuel efficiency improvements up to 10% [30,31]. BMW TGM may be available in 2018 [32]. Ford's version is shown in Fig. 3(b) [33].

Due to the physical layout of the TGM TERSs, which involves heat transfer from exhaust to coolant, there are additional indirect benefits such as fast engine warm up and downsizing of the exhaust. On the other hand, the system requires a higher complexity of the exhaust/coolant configuration, an oversized radiator, an increased weight and greater space, which makes a retrofit version difficult to apply. This technique may increase as well the back pressure of the exhaust, which tends to reduce the performance of the engine [31,34].

2.1.1.2. Rankine cycle TERS. This system uses a Rankine cycle to convert the thermal energy in the exhaust into mechanical energy. The heat of the exhaust increases the temperature of a fluid until it boils. As a consequence, a steam is produced which is used to power a turbine. The energy provided by the turbine is in mechanical form, so it can be used to generate electricity or to deliver torque to the powertrain, as shown in Fig. 4. A number of configurations have been proposed, including single and dual loop cycles and different fluids [29,35,36].

Honda and BMW are major manufacturers developing Rankine cycle TERSs. BMW have claimed that the definitive version will weigh no more than 15 kg. Average gains in fuel consumption are estimated from 10% to 15% [29,36].

The need of interchangers, condensers, evaporator, turbines and piping, along with their interaction with the existing parts of the vehicle add complexity to this ERS technique. This fact, together with the additional space required, makes a retrofit option difficult to implement.

2.1.2. Kinetic energy recovery from exhaust gases

During the operation of an ICE, gases at high velocity are released through the exhaust. Part of the kinetic energy (KE) contained in these gases can be recovered by a turbine generator (TG) and converted into electrical energy [37]. These ERSs are normally termed as Electric Turbo Compound (ETC) [38,39], although because of the thermal phenomena some studies still classify this type of technique as TERS [36,39]. Fig. 5 shows the layout of an ETC ERS (a) and an ETC prototype (b) from [40].

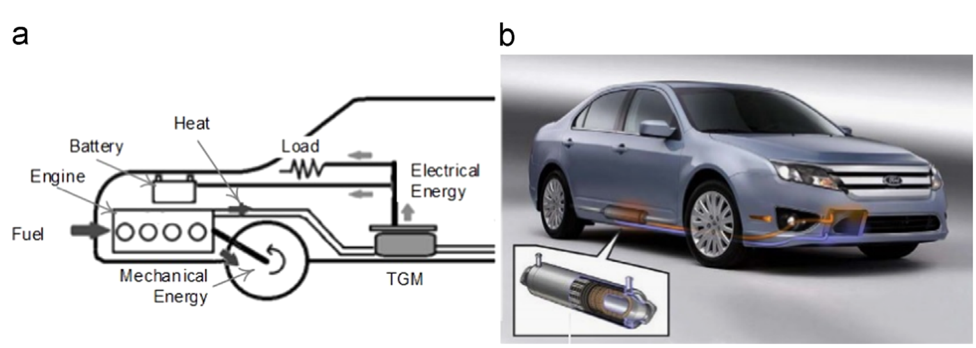

Fig. 3. (a) TGM TERSs layout. The energy of the vehicle comes from the fuel. The engine turns part of this energy into useful mechanical energy to the wheels, but a great amount is lost as a heat in the exhaust. The TGM converts part of this wasted thermal energy into electricity, feeding the electrical consumers of the vehicle (load) or charging the battery. (b) Ford TERS proposed system, placing the TGM in the middle section of the exhaust.

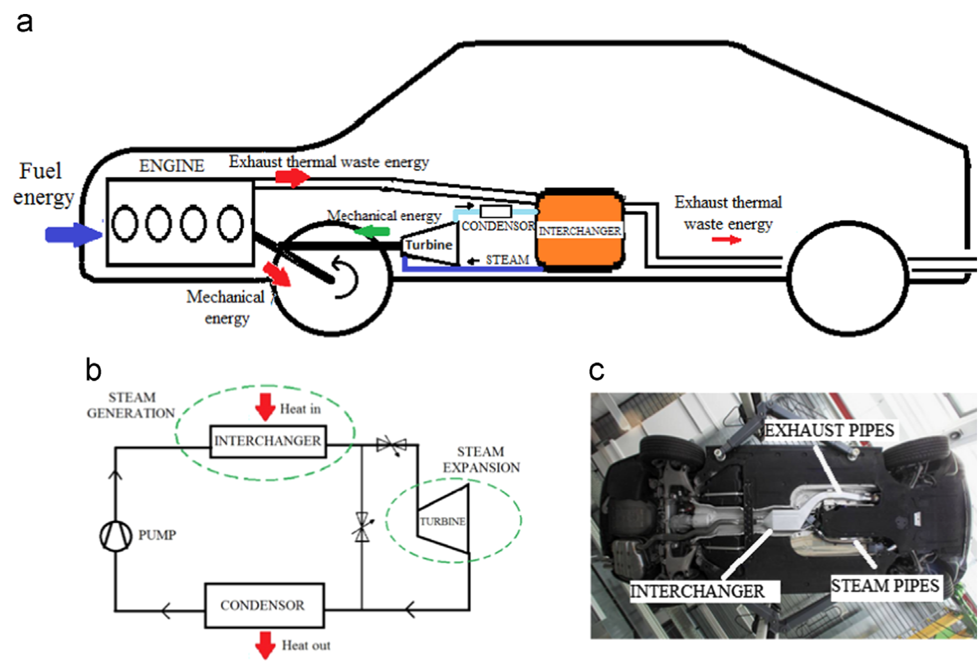

Fig. 4. (a) Rankine cycle TERSs layout. The thermal energy lost through the exhaust is used to heat a fluid in an interchanger. The steam produced powers a turbine, which aids the engine to propel the car. Steam is further condensed to continue the Rankine cycle. (b) Single loop Rankine cycle illustrated. (c) BMW's system in test vehicle, adapted from [29].

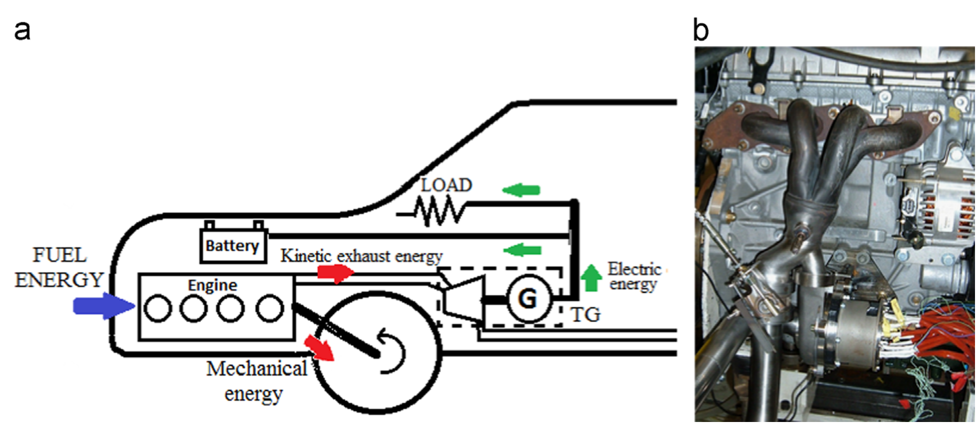

Fig. 5. (a) ERS ETC layout. Waste exhaust gases reach the TG unit from the engine. Part of the kinetic energy of the gases is recuperated for the unit and converted into electrical energy. This electrical energy is then used to feed the consumers of the vehicle (load) or to charge the battery. (b) An ETC prototype [40].

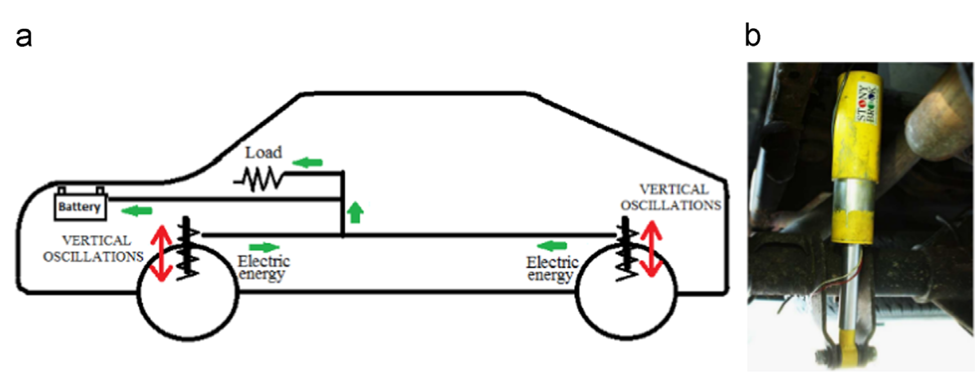

Fig. 6. (a) Layout of ERS from vertical oscillations. Part of the KE of the vertical movements of the body is recovered by the RSA, placed next to the wheels. RSA transform this energy into electricity, which is used to feed the electrical loads of the vehicle or to charge the battery. (b) RSA fitted in a vehicle for testing.

Simulations of ETCs have shown fuel efficiency improvements of around 5%, although under specific conditions, a decrease in efficiency of 1% may occur [39]. Companies, such as CPOWERT, have already prototypes in advanced stage of development, which claims a more efficient generation of electricity than the conventional alternator found in an ICEV. It is expected that ETC will be

available in 2016 [41]. The power of the CPOWERT ETC is 6 kW, weights 6 kg and length is 150 mm. Due to the high working temperatures, the liquid cooling system is necessary [40]. The main obstacle for a retrofit version might be the integration of the TG with the exhaust and cooling system of the vehicle.

2.2. *Energy recovery from vertical oscillations*

Part of the KE associated with the vertical oscillations of the vehicle body during driving, such as bumping, can be recovered with regenerative shock absorbers (RSAs). RSAs transform the KE into electricity, which may be used for the electrical auxiliaries or stored in the battery. Fig. 6(a) illustrates a typical layout of the system. Different technologies have been proposed for the RSA, including specific configurations for retrofitting purposes. Prototypes have been already tested. The average improvement in the vehicle efficiency recorded ranges from 2% to 10% [33,42–44].

Parameters of influence for the efficiency of this ERS technique are the type of vehicle and road. In this way, heavy vehicles and rough surfaces seem advantageous. The rate of energy recovered ranges from 100 to 400 W for a LDV, although for heavy duty vehicles (HDVs) it could be 25 times higher [42]. Fig. 6(b) shows an RSA fitted in a test vehicle.

This technique presents good characteristics for retrofitting in any vehicle and the potential savings in fuel are significant. However, the need to fit more than one shock absorber, one per wheel, and the replacement intervals these components are subjected at, may have a negative impact in the cost. In addition, the nature of the energy source could make the system more appropriate for off-road conditions and trucks rather than LDVs.

2.3. *Energy recovery from vehicle inertia*

The most common source of energy recovery is the inertia of the vehicle due to its speed. When deceleration is needed, a force has to be applied to overcome the inertia of the vehicle. This is normally done by the braking system, which reduces the speed of the vehicle by converting part of its KE into waste heat in the brakes. However, a fraction of that KE can be recuperated and stored. This stored energy may be used again, normally under acceleration, thus reducing high demands on the engine and consequently lowering fuel consumption. ERSs based on vehicle inertia are termed as kinetic energy recovery systems (KERSs). As these systems recover the energy mainly during braking events, the process of energy recovery is termed regenerative braking (RB).

There are different types of KERS, with variations in recovery and storage technologies. However, all KERSs share the same advantage and disadvantage. The advantage is that due to the great weight and speed of LDVs, they have associated a high momentum. Therefore, a great amount of energy can be potentially recovered. The disadvantage is that the energy is not recoverable continuously, but during short periods, typically during braking events. This fact makes the gains obtained by these systems sensitive to driving conditions. Urban driving, with frequent decelerations, is a favorable condition, as opposed to motorway driving. Fig. 7 shows a diagram illustrating the working principle of a KERS.

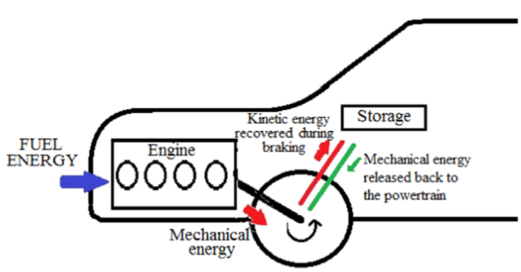

Fig. 7. KERS general layout. The engine transforms part of the fuel energy into mechanical energy to the wheels. As a consequence, the vehicle moves, therefore having a KE associated. A fraction of this KE can be recovered and stored, mainly during braking events. In turn, the energy stored can be released back, which is normally done during acceleration.

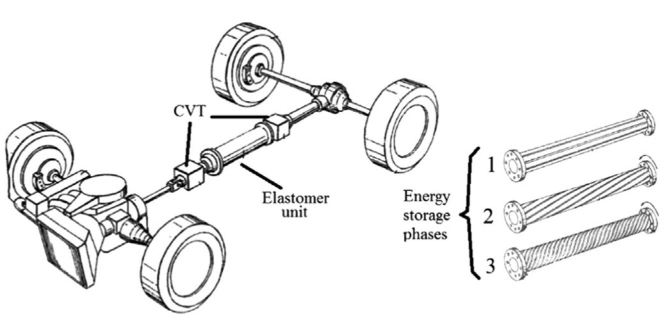

Fig. 8. Configuration of an elastomer KERS [45]. The elastomer is located between engine and driven wheels. A CVT unit controls the energy transfer. The drawing on the right illustrates the deformation of the elastomer as it stores energy. Process is reverted when energy is released.

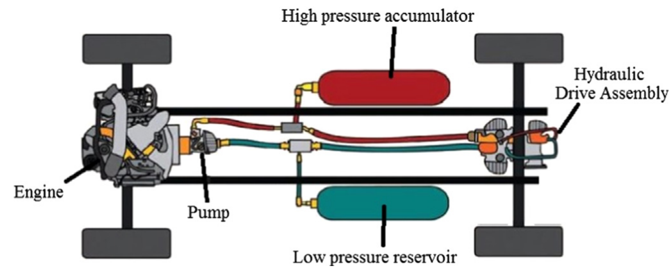

Fig. 9. Configuration of a hydraulic KERS [51]. Under deceleration, the pump stores the fluid at high pressure in the accumulators. When needed, power is released back from the accumulators to the wheels through the hydraulic drive assembly. Pump is driven by the powertrain.

2.3.1. *Spring and elastomers KERS*

Spring and elastomer KERS store the energy during RB as potential elastic energy. This is done by elastically deforming an elastomer or metallic spring. They can go back to their initial shape when power is needed, releasing part of the absorbed energy. In order to regulate the energy transfer, a continuous variable transmission (CVT) may be required [45–47]. The volume of elastomer needed has been estimated around 45 l [47,48]. Simulations carried out in a spring KERS performing CVT and capable of storing 30 kJ have achieved a potential fuel efficiency improvement of 15% [46]. A typical configuration of the system is illustrated in Fig. 8.

The operation of this type of KERS is purely mechanical, therefore there are no losses associated to energy conversion. Moreover, the energy can be stored for a longer duration. On the other hand, they need a significant space to be fitted, and they typically require a CVT, which adds complexity and weight to the system. There is a lack of recent literature on the topic.

2.3.2. *Pneumatic and hydraulic vehicle inertia KERS*

In these systems, the KE of the vehicle is stored by increasing the pressure of a fluid. In a pneumatic type, air is stored in tanks whereas, in a hydraulic system, a non-compressible fluid is stored in accumulators. The energy is released back to the powertrain by decreasing the pressure of the fluid. Fig. 9 shows a design for a hydraulic type.

Simulations of a pneumatic KERS with 400 kJ of energy storage have shown a maximum fuel efficiency improvement of 25%. In

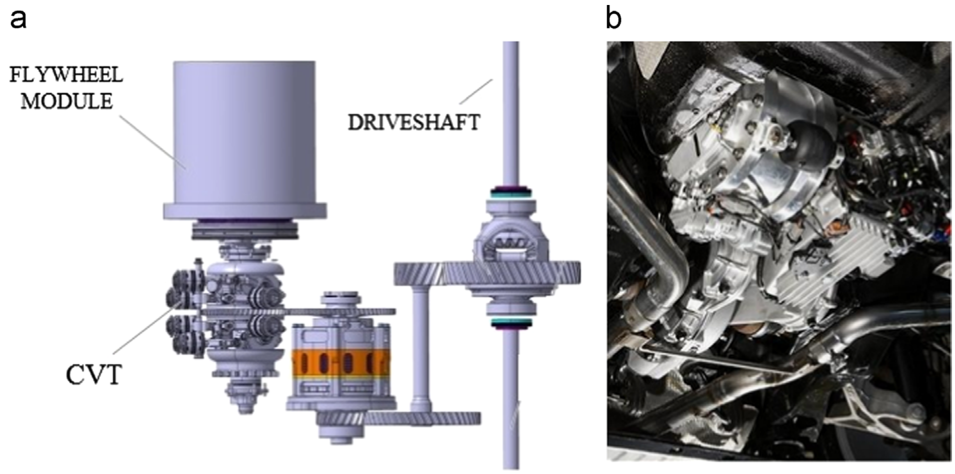

Fig. 10. (a) Main components of a Volvo flywheel KERS [56]. Under deceleration, the energy comes from the driveshaft (connected to the wheels) to the flywheel module. The speed and energy stored by the flywheel is controlled for a CVT. Reverse process for acceleration. Energy is always in mechanical form. (b) Flywheel KERS installed in a test-car.

the same way, a hydraulic KERS with 90 kJ of energy storage has demonstrated up to 35% increase in fuel efficiency [49]. For a pneumatic type, it has been estimated that a 1-ton vehicle would require a storage tank of 30 l [50].

These systems present a great potential for fuel reduction and the cost is potentially lower than electric based systems [50]. However, the additional space and added weight of tanks and accumulators make this KERS option more suitable for heavy vehicles rather than LDV. In addition, they may require major modifications in the powertrain, making them difficult to retrofit.

2.3.3. Flywheel KERS

This technique stores the KE of the vehicle as rotational energy by increasing the angular velocity of a flywheel. Fuel consumption reductions from 20% to 30% are potentially achievable. However, the energy recovered cannot be permanently stored, due to the friction on the flywheel. To develop its full potential the system may need a CVT, a composite flywheel spinning at 60,000 revolutions per minute (rpm), vacuum chamber and magnetic bearings. These are high-technology components which increase the cost and complexity of the system. In spite of that, flywheel techniques are claimed to be cheaper than an equivalent electric KERS. The total weight is around 65 kg for a 1800 kg vehicle. Average values for power and energy storage of the system are around 60 kW and 580 kJ respectively [53–55]. Fig. 10 shows the configuration of a flywheel KERS and a unit installed in a testing vehicle [56].

Flywheel KERSs have already been well proven in motorsport, namely in Formula 1. A number of major car manufacturers, such as Jaguar and Volvo, are currently developing this technology for LDV, which could be on production by 2015. While a retrofit version is technically possible, size and weight restraints, cost and complexity could make it more suitable for heavy vehicles. Despite the number of companies developing this system, the preference of vehicle manufacturers for electric KERS to develop their hybrid models suggest that the potential advantages of this technique are not easy to realize [54].

2.3.4. Electric KERS

Electric KERS turn part of the KE of the vehicle into electricity by means of a motor-generator (MG), and store it in batteries. They can be divided into two main groups: strong/mild electric KERS and alternator-control based KERS.

2.3.4.1. Strong/mild electric KERS. These systems are utilized in the current generation of HEVs. Different configurations of the system are illustrated in Fig. 11. In a “strong” or “full” HEV, like the Toyota Prius, Fig. 11(a), the energy recovered during RB by the MG is stored in a large battery pack. The MG provides torque to aid the engine and even it is able to propel the car on its own at low speed [57]. There are losses associated to the energy transformation path (mechanical–electric–chemical) from the wheels to the battery and vice-versa, which reduce the efficiency of the technique. However, these systems are able to achieve up to 40% fuel improvement [53]. The cost of the batteries, complexity, weight, and space constraints makes this method difficult to retrofit.

A mild version of this system consists of smaller batteries and less powered MG. There are two main different configurations for mild KERS. The first configuration is known as integrated, as the MG is integrated between engine and gear box, as shown in Fig. 11(b). The second configuration is known as a belted type, as the MG generator is belt-driven by the engine. In this case the MG is located as an ancillary on the side of the engine, substituting the alternator of the vehicle, as shown in Fig. 11(c). Fuel improvements over 10% are achievable with belted mild electric KERS [58] which at the same time presents good retrofitting characteristics, as a result of its location. Integrated mild KERS may achieve up to 22% fuel improvement [59], but due to the integrated design, a retrofit version involves high cost and complexity.

2.3.4.2. Alternator-control KERS. Alternator-control KERS technique, shown in Fig. 12, manages the alternator of the vehicle in a more efficient way than conventional systems. Typically, the alternator output is increased during braking events, using the KE of the vehicle to maximize the energy storage in the battery and feed the electrical consumers. During acceleration, the alternator output is reduced and the consumers are fed by the energy stored in the battery. Therefore the engine power demand is reduced and fuel is saved.

Main manufacturers such as BMW and Renault currently offer this system in a number of models [6,7], and a retrofit version has been already proposed [60]. Efficiency improvement ranges from 1% to 5% [6,61,62]. The technique allows the use of standard components, but special monitoring of the battery among other parameters is needed for an accurate management of the system [63]. Fig. 12(b) shows an Intelligent Battery Sensor (IBS), used for this task.

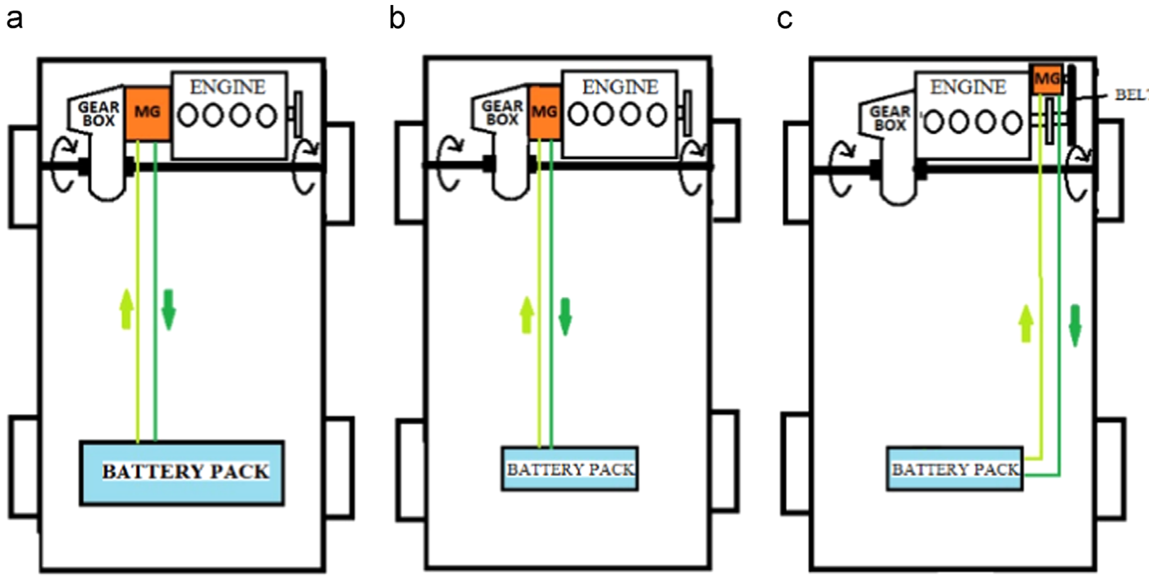

Fig. 11. Different configurations of strong/Mild Electric KERS. Strong/Mild Electric KERSs (a) Strong/full, (b) mild integrated and (c) mild belted. In all cases the working principle is the same. KE energy is recuperated from the drive train by the MG, which is stored in batteries. When the energy is needed the process is reverted.

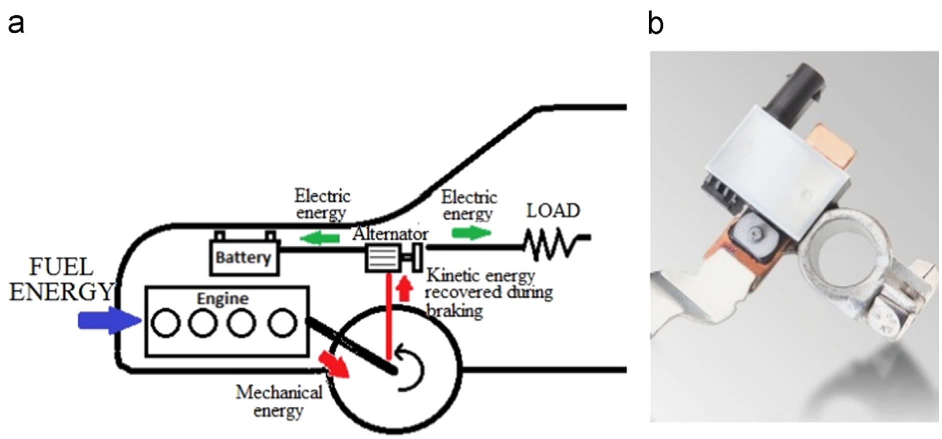

Fig. 12. (a) Alternator-control KERS layout. The KE of the vehicle is used for the alternator to produce electrical energy at its maximum output. This energy is used to charge the battery and feed the consumers. (b) Hella intelligent battery sensor (IBS) [63,64].

Table 1
Comparison of ERSs. Efficiency gain: (3) over 25%, (2) 10–25%, (1) under 10%. Weight and space: (1) no significant space or weight added, (2) moderate extra space required or weight added (typically < 40 kg), (3) considerable space required or weight added (> 40 kg). Energy recovery: (1) only under deceleration, (2) depending of road surface, (3) continuously. Retrofit-ability: (1) difficult, (2) medium, (3) easy. N/A: not available. Table based in data from: [29–31,36,39,40,42,46,48–50,53,54,57–59,61,62].

Technique	*Type of energy*			*Parameters*					
	Source	**Storage**	**Release**	**Efficiency gain**	**Space and weight**	**Energy recovery**	**Hybrid Capability**	**Maturity**	**Retrofit-ability**
Thermo electric TERS	Thermal	Chemical	Electric	2	2	3	No	2018	2
Rankine cycle TERS	Thermal	Mechanical (steam)	Electric-mechanical	2	2	3	Yes	2018	1
Electric turbo compound (ETC)	Kinetic	Chemical	Electric	1	2	3	No	2016	2
KERS from vertical oscillations	Kinetic	Chemical	Electric	1	1	2	No	N/A	3
Elastomer or spring KERS	Kinetic	Mechanical (elastic)	Mechanical	2	3	1	Yes	N/A	1
Pneumatic or hydraulic KERS	Kinetic	Mechanical (pressure)	Mechanical-Electric	3	3	1	Yes	N/A	1
Flywheel KERS	Kinetic	Mechanical (rotation)	Mechanical	3	3	1	Yes	2015	1
Strong electric KERS	Kinetic	Chemical	Mechanical-Electric	3	3	1	Yes	Available	1
Mild electric KERS	Kinetic	Chemical	Mechanical-Electric	2	2	1	Yes	Available	2
Alternator control KERS	Kinetic	Chemical	Electric	1	1	1	No	Available	3

Table 2
Main advantages and disadvantages for ERSs.

Technique	Advantages	Disadvantages
Thermo electric TERS	Continuous energy recuperation Faster engine warm-up Exhaust system can be downsized	Engine performance slightly reduced No hybrid capability
Rankine cycle TERS	Continuous energy recuperation Hybrid capability	Complexity Difficult to retrofit. Energy cannot be stored permanently
Electric turbo compound (ETC)	Continuous energy recuperation Moderately easy to retrofit Low added weight and space	Moderated gains in efficiency No hybrid capability Need of cooling adds complexity
KERS from vertical oscillations	Easy to retrofit No space or significant weight added	Low efficiency improvement Best results for heavy and off-road vehicles No hybrid capability. RSA subject to wear
Elastomer or spring KERS	Purely mechanical, no losses for energy conversion Hybrid capability	Complex. Heavy. Requires CVT. Difficult to retrofit Currently not being developed Energy recovery only during short periods
Pneumatic or hydraulic KERS	High efficiency improvement. Hybrid capability Not as costly as other ERSs with similar efficiency	Difficult to retrofit. Pneumatic type can be noisy. Heavy, bulky, best suited for heavy vehicles Energy recovery only during short periods
Flywheel KERS	High efficiency improvement. Hybrid capability Technology well proven in motorsport	Complex, costly, difficult to retrofit. Energy cannot be stored permanently Energy recovery only during short periods
Strong electric KERS	High efficiency improvement Proven technology, already available Hybrid capability	Complex, difficult to retrofit. Heavy, costly Losses due to energy transformation processes Energy recovery only during short periods
Mild electric KERS	Proven technology already available. Belted-type moderately easy to retrofit Hybrid capability	Integrated type difficult to retrofit Losses due to energy transformation processes Energy recovery only during short periods
Alternator-control KERS	Easy to retrofit. Inexpensive. Proven technology, already available No space or significant weight added Use of standard components possible	Low efficiency improvement Energy recovery only during short periods No hybrid capability

The amount of energy recovered with this system is obviously low compared with other KERS and consequently, efficiency improvements are moderated. On the other hand, it allows for excellent retrofitting properties, since there are not any new major parts necessary for its implementation, so complexity, cost and space requirements are kept low.

3. Comparison of ERS

Main characteristics of ERSs are summarized in Table 1, while typical advantages and disadvantages for each system are shown in Table 2. Due to the high number of ERSs analyzed, numerical data is from different sources, including simulations, prototype testing and manufacturers' information. Therefore, a qualitative approach is best suited to show the results. The comparison summary has to be taken in the context of assumptions.

4. Conclusion

In this comprehensive review, the most relevant ERSs for ICEVs were analyzed, giving special attention to fuel efficiency gains and retrofit capabilities. ERSs come in a wide variety of technologies and only few are readily available to date. Mass deployment is still hampered by their investment cost. As ICE technology will predominate in the short–medium term, ERSs for ICEVs may be considered one of the best carbon cutting measures for the automotive sector. Although, an increased number of new vehicles are being equipped with these systems, the fact that majority of the current vehicle parc lacks this feature raises the possibility of a retrofit version. By retrofitting existing ICEVs, significant savings in global emissions and fuel consumption can be achieved.

It has been identified that the best ERSs in terms of fuel efficiency gain are the most difficult to retrofit. However, in the context of the study, the most suitable ERS may not be the one providing the best retrofit characteristics or the highest efficiency improvement. Other factors need to be taken into consideration, such as annual mileage, age and residual value of the vehicle. With an average age of cars around 7 years and a lifetime of 15 years, the selection of a high-efficiency retrofit ERSs may not be suitable. To obtain high gains in fuel usage, these systems require major new parts and modifications in the vehicle, with elevated costs associated. The price of retrofitting the ERSs could be in the same order of magnitude than the residual value of the car, being very unlikely for the owner to install the system. Therefore, a retrofitting ERS requires a good compromise between efficiency gains and cost, so they can pay back its price in a short period of time. In this way, they would be able to reduce GHG emissions while being economically feasible to the end-user.

Further research is needed to investigate the trade-off between fuel consumption reduction and investment cost of the system.

References

[1] EU-DG-TREN, EU energy in figures 2010, CO_2 Emissions by Sector, European Commission directorate general for energy and transport; 2010.
[2] EU-FTE, How clean are Europe's cars? An analysis of carmaker progress towards EU CO_2 targets in 2009, European Federation for Transport and Environment; 2010.
[3] Hoppie LO. Elastomeric regenerative braking systems. Warrendale, PA: SAE International; 1983 (830112).
[4] Tollefson S, Beachley NH, Fronczak FJ. Studies of an accumulator energy-storage automobile design with a single pump/motor unit. Warrendale, PA: SAE International; 1985 (851677).
[5] Dispositif pour emmagasiner et resituer de l'energie et application a la propulsion d'un vehicule/ Bommer Raymond: Patent FR 2 278 945 A1, 13.02.1976.

[6] BMW AG. BMW brake energy regeneration. Available from: 〈http://www.bmw.com/com/en/insights/technology/efficientdynamics/phase_1/measures_brake_energy_regeneration.html〉; 2012 [accessed Jun 2012].
[7] Renault. Renault innovation official site. Available from: 〈http://www.renault.com/en/innovation/gamme-mecanique/pages/energy-dci-110.aspx〉; 2012 [accessed Sep 2012].
[8] Toyoya UK. Hybrid sinergy drive. Available from: 〈http://www.toyota.co.uk/cgi-bin/toyota/bv/generic_editorial.jsp?navRoot=toyota_1024_root&noLeftMenu=true&fullwidth=TRUE&nodiv=TRUE&edname=HybridFamily-landing&id=Nav_HSD&zone=Zone+See+the+Range&sr=Mall〉; 2013 [accessed Jan 2013].
[9] Nissan UK. The language of LEAF. Available from: 〈http://www.nissan.co.uk/GB/en/YouPlus/emags/EV/the_language_of_leaf.html〉; 2013 [accessed Jan 2013].
[10] Next Greencar. Hybrid cars becoming more mainstream. Available from: 〈http://www.nextgreencar.com/news-item.php?Hybrid-cars-becoming-more-mainstream〉; 2012 [accessed Dec 2012].
[11] Society of motor manufacturers and traders. New car CO_2 report 2012. Available from: 〈http://www.smmt.co.uk/wp-content/uploads/SMMT-New-Car-CO2-Report-2012.pdf〉; 2013 [accessed Jan 2013].
[12] IEA, Transport, Energy and CO_2, International Energy Agency, 78-92-64-07316-6; 2009.
[13] European automobile manufacturers association. The automotive industry pocket guide; 2012.
[14] Hawkins TR, Gausen OM, Strømman AH. Environmental impact of hybrid and electric vehicles – a review. Int J Life Cycle Assess 2012;17(8):997–1014.
[15] Hybrid vs. Diesel iCar Magazine article. Issue 1; Jul 2011.
[16] Sweeting WJ, Winfield. PH. Future transportation: lifetime considerations and framework for sustainability assessment. Energy Policy0301-4215 2012;51:927–38.
[17] Howey DA, Martinez-Botas RM, Cussons B, Lytton L. Comparative measurements of the energy consumption of 51 electric, hybrid and internal combustion engine vehicles. Transp Res Part D Transp Environ 2011;16(6):459–64.
[18] Larminie J, Lowry J. Electric vehicle technology explained. West Sussex, England: John Wiley & Sons, Ltd.; 2003.
[19] O. Inderwildi, Future of mobility roadmap ways to reduce emissions while keeping mobile, (white paper). University of Oxford Smith School of Enterprise and the Environment; 2011. p. 2042–4043.
[20] Schelmetic T. Are hybrid vehicle manufacturers shifting gears away from rare earth elements?. Thomas net news, December. Available from: 〈http://news.thomasnet.com/green_clean/2012/12/11/are-hybrid-vehicle-manufacturers-shifting-gears-away-from-rare-earth-elements/〉; 2012 [accessed Feb 2013].
[21] Jamasmie C. Brazil a step closer to fully mine the Amazon. Available from: 〈http://www.mining.com/brazil-a-step-closer-to-fully-mine-the-amazon-70962/〉; September 2012 [accessed Feb 2013].
[22] STOP LYNAS. Available from:〈 http://stoplynas.org/〉; December 2012 [accessed Feb 2013].
[23] EU, Clean power for transport – frequently asked questions. Available from: 〈http://europa.eu/rapid/press-release_MEMO-13-24_en.pdf〉; Jan 2013 [accessed Mar 2013].
[24] Auto Trader UK. Car scrappage scheme: complete guide Available from: 〈http://www.autotrader.co.uk/EDITORIAL/CARS/FEATURES/get_2000_pounds_off_your_next_car.html〉; December 2012 [accessed February 2013].
[25] Kagawa S, Nansai K, Kondo Y, Hubacek K, Suh S, Minx J, et al. Role of motor vehicle lifetime extension in climate change policy. Environ Sci Technol 2011;45(4):1184–91.
[26] Kagawa S, Nansai K, Kudoh Y. Does product lifetime extension increase our income at the expense of energy consumption? Energy Econ 2009;31(2):197–210.
[27] Tahani M, Javan S, Biglari M. A comprehensive study on waste heat recovery from internal combustion engines using organic Rankine cycle. Tehran, Iran: Faculty of New Sciences and Technologies (FNST), Tehran University; 2012.
[28] Obieglo A,Ringler J, Seifert M, Hall W. Future efficient dynamics with heat recovery, BMW group research and technology. Available from: 〈http://www1.eere.energy.gov/vehiclesandfuels/pdfs/deer_2009/session5/deer09_obieglo.pdf〉; 2009 [accessed Sep 2012].
[29] BMW Group. Looking for the next gram. BMW press release. Available from: 〈www.press.bmwgroup.com/pressclub/p/pcgl/pressDetail.html?outputChannelId=6&id=T0119738EN&left_menu_item=〉; Aug 2008 [accessed May 2012].
[30] Yang J. Opportunities and challenges of thermoelectric waste heat recovery in the automotive industry. GM research and development center. Available from: 〈http://www1.eere.energy.gov/vehiclesandfuels/pdfs/adv_engine_2005/2005_advanced_engine_4.pdf〉; 2005 [accessed May 2012].
[31] LaGrandeur J, Crane D. Vehicle fuel economy improvement through thermoelectric waste heat recovery. Available from: 〈http://www1.eere.energy.gov/vehiclesandfuels/pdfs/deer_2005/session6/2005_deer_crane.pdf〉; 2005 [accessed May 2012].
[32] Eder A, Linde M. Efficient and dynamic – the BMW group roadmap for the application of thermoelectric generator BMW group. Available from: 〈http://www1.eere.energy.gov/vehiclesandfuels/pdfs/thermoelectrics_app_2011/monday/eder.pdf〉; 2011 [accessed Jan 2013].
[33] H. Zervos. Energy harvesting for automotive applications (white paper) IDTechEx Ltd.; 2011.
[34] Francis Stabler, automotive thermoelectric generator design issues. Available from: 〈http://www1.eere.energy.gov/vehiclesandfuels/pdfs/thermoelectrics_app_2009/wednesday/stabler.pdf〉; 2009 [accessed Feb 2013].
[35] Hounsham S, Stobart R, Cooke A, Childs P. Energy recovery systems for engines. Warrendale, PA: SAE International; 2008 (2008-01-0309).
[36] Vining CB. An inconvenient truth about thermoelectrics. Nat Mater 2009;8(2):83–5.
[37] Dunn RJ. Waster energy recovery and alternative energy storage. Available from: 〈http://www2.warwick.ac.uk/fac/sci/wmg/research/lcvtp/documents/presentations/lcvtp046-paper6disseminationevent21.09.11-ws11-wasteenergyv2-memorystick.pdf〉; 2011 [accessed Feb 2013].
[38] Vuk CT. Electric turbo compounding. a technology who's time has come. John Deere Technical Center. Available from: 〈https://www1.eere.energy.gov/vehiclesandfuels/pdfs/deer_2006/session6/2006_deer_vuk.pdf〉; 2006 [accessed Feb 2013].
[39] Zhuge W, Huang L, Wei W, Zhang Y, He Y. Optimization of an electric turbo compounding system for gasoline engine exhaust energy recovery. Warrendale, PA: SAE International; 2011 (2011-01-0377).
[40] CPOWERT. TIGERS. Available from: 〈http://www.cpowert.com/products/tigers.htm〉; 2012 [accessed May 2012].
[41] New automotive innovation and growth team (NAIGT), An independent report on the future of the automotive industry in the UK; 2009.
[42] Zuo L. Energy harvesting shock absorbers. Available from: 〈http://www.aertc.org/conference2011/Speaker%202011/2011%20AEC%20Session%205/5B%20Advanced%20Transportation/Lei%20Zuo/3%29%20B%20Track,%205%20Session%20Lei%20Zuo%202011.pdf〉; 2011 [accessed May 2013].
[43] Wang J, Guo X, Su Y. The shock absorber of energy recovery using electro-rheological fluid. Warrendale, PA: SAE International; 2012 (2012-01-0981).
[44] Xu L. Structure designs and evaluation of performance simulation of hydraulic transmission electromagnetic energy-regenerative active suspension. Warrendale, PA: SAE International; 2011 (2011-01-0760).
[45] Gill JD, Elastomeric energy recovery system, United States Patent PAT-APPL-3520814479356; 30 October 1984.
[46] Tchobansky L, Kozek M, Schlager G, Jörgl HP. A purely mechanical energy storing concept for hybrid vehicles. Warrendale, PA: SAE International; 2003 (2003-01-3278).
[47] Kirby HR, Clegg SJ, Crolla DA, Duckett RA, Dougherty MS. An elastomeric energy storage system to improve vehicle efficiency, Institute for Transport Studies. University of Leeds, ITS Working Paper 491; April 1997.
[48] Hoppie LO. Elastomeric regenerative braking systems. Warrendale, PA: SAE International; 1983 (830112).
[49] Barr A, Veshagh A. Fuel economy and performance comparison of alternative mechanical hybrid powertrain configurations. Warrendale, PA: SAE International; 2008 (2008-01-0083).
[50] Schechter MM. Regenerative compression braking – a low cost alternative to electric hybrids. Warrendale, PA: SAE International; 2000 (2000-01-1025).
[51] Brighthub engineering. What are hydraulic accumulators? How do they work? Available from: 〈http://www.brighthubengineering.com/hydraulics-civil-engineering/43410-hydraulic-accumulators-theory-and-use/〉 [accessed Feb 2013].
[53] Boretti A. Improvements of vehicle fuel economy using mechanical regenerative braking. Warrendale, PA: SAE International; 2010 (2010-01-1683).
[54] Volvo Cars. News – press releases & media updates. Available from: 〈http://www.volvocars.com/uk/top/about/news-events/pages/default.aspx?itemid=110〉; 2013 [accessed Feb 2013].
[55] Williams Gran Prix Engineering Limited. Williams hybrid power. Available from: 〈http://www.williamshybridpower.com/technology/whps-flywheel-technology〉; 2013 [accessed Feb 2013].
[56] Gizmaz automotive. Volvo touts mechanical KERS for future road cars. Available from: 〈http://www.gizmag.com/volvo-touts-mechanical-kers-technology-for-road-cars/18772/〉; 2012 [accessed Feb 2013].
[57] Eshani M, Gao Y, Emadi A. Modern electric, hybrid electric and fuel cell vehicles. 2nd ed. Boca Raton: CRC Press; 2010.
[58] Walters JE, Krefta RJ, Gallegos-Lopez G, Fattic GT. Technology considerations for belt alternator starter systems. Warrendale, PA: SAE International; 2004 (2004-01-0566).
[59] Gao Y, Ehsani M. A mild hybrid vehicle drive train with a floating stator motor-configuration, control strategy, design and simulation verification. Warrendale, PA: SAE International; 2002 (2002-01-1878).
[60] Asada T, Maeda S. A stand-alone charging management system to improve fuel economy, based on an algorithm of estimating vehicle motion. Warrendale, PA: SAE International; 2008 (2008-21-0045).
[61] Surampudi B, Redfield J, Ostrowski GJ. Mild regenerative braking to enhance fuel economy via lowered engine load due to alternator. Warrendale, PA: SAE International; 2008 (2008-01-2560).
[62] Brabetz L, Ayeb M, Tellmann D. Efficient vehicle power supply by adaptive energy, charge and heat management of an alternator – super capacitor system. Warrendale, PA: SAE International; 2009, 2009-01-1094.
[63] Heim A, Streibl. T. The intelligent battery sensor: key component for a scaleable motor-vehicle-independent energy management system. Warrendale, PA: SAE International; 2006-21-0001.
[64] Hella. Intelligent battery sensor. Available from: 〈http://www.hella.com/microsite-electronics/assets/media/IBS_April_2013_rz.pdf〉; 2013. [accessed Jan 2014].